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Title: Estimation of human power output from maximal vertical jump and body mass

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Running head: Estimation of power output from vertical jump

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ABSTRACT

The Lewis formula and nomogram, published in widely distributed textbooks, are used to calculate power output from vertical jump-and-reach distance and body weight. Despite the fact that the method has never been supported by a refereed journal publication and the texts never revealed whether peak or average power was being estimated, the test has become increasingly used by physical educators, coaches and researchers. Theoretical analysis has raised questions about the formula's validity. In order to evaluate the test, Lewis formula derived power output was compared to peak power and average power generated by 17 male subjects jumping vertically from a computer-interfaced force plate. Lewis power, peak power and average power (mean \pm SD) were $1,107\pm144$, $3,767\pm686$ and $1,325\pm341$ watts respectively. The low standard deviation for Lewis power suggests the formula minimizes individual differences. Lewis power respectively correlated 0.83 and 0.72 with peak and average power but underestimated them by $70.1\pm3.5\%$ and $12.4\pm18\%$. The following regression-derived equations whose respective r's were 0.88 and 0.73 better estimate peak and average power than does the Lewis formula and produce respective standard deviations of 603 W and 247 W, which more closely reflect actual inter-subject variability:

$$\text{Peak power(W)} = 61.9(\text{jump height(cm)}) + 36.0(\text{body mass(kg)}) + 1,822$$

$$\text{Avg. power(W)} = 21.2(\text{jump height(cm)}) + 23.0(\text{body mass(kg)}) - 1,393$$

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Use of the Lewis formula should be discontinued because it does not provide accurate estimates of either peak or average power produced by the muscles. While the force-platform technique remains the method of choice for precise jumping-power determinations in the laboratory, the above equations can be used in conjunction with other tests to screen applicants for athletic teams and physically demanding jobs, and to monitor progress among participants in physical training programs.

Very truly yours,
LEWIS FORMULA, FORCE PLATFORM, TESTS; C.K.

INTRODUCTION

The ability to generate high human power output is instrumental to performance in many sports and physically demanding work activities. A convenient, valid, and reliable power output test would enhance any battery used for entry-screening or progress-evaluation of athletes, manual workers, fitness program participants, and military personnel.

An estimate of the power generated during an activity can provide insight beyond that given by the performance itself (e.g. distance jumped, weight lifted). For example, two individuals of different body weight might be able to jump vertically the exact same distance. However, the heavier individual's jump would show the ability to generate greater power, which could provide an advantage in activities which involve manipulation of mass outside the body (e.g. baseball batting, putting the shot, football blocking, weight lifting).

An individual's power output during a test is dependent on the joint range of motion, muscle groups involved, and movement type (concentric, eccentric, single-joint, multi-joint, flexing, extending, slow, fast, isokinetic, accelerating, etc.). Therefore, a single number cannot adequately describe an individual's power output capability. To be useful, a test should measure power output during a type of movement of interest to the evaluator, such as one similar to a physical activity the subject must perform in work or sport (6). Jump testing is potentially very useful

because many sports and work activities involve either jumping or movements similar to jumping, such as lifting heavy objects ballistically. Jumping primarily involves the gluteal and quadriceps muscles, which are instrumental in many sport and work activities.

The Lewis formula, and nomogram based on the formula, have become widely used among coaches, physical educators, and researchers to estimate power output during the vertical jump-and-reach test (1,8). According to the formula,

$$\text{POWER}_{\text{kg-m/s}} = \sqrt{4.9 \cdot \text{WEIGHT}_{\text{kg}} \cdot \text{JUMP-REACH SCORE}_{\text{m}}} \quad (1)$$

The formula and nomogram appear to have been first published in 1974 in a book on interval training by Fox and Mathews (4). The only reference provided for the formula was a note stating "Courtesy, Office of Naval Research". The formula and nomogram were popularized in the 1976 and 1981 editions of the widely used exercise physiology textbook by Fox and Mathews (3,7), and have been more recently published in a book on tests and measurements for physical educators (5).

A phone conversation with Dr. Mathews revealed that he developed the formula and nomogram in conjunction with his student, Mr. Lewis. Development of the nomogram was funded in part by the Office of Naval Research.

An obvious problem with the formula is that it does not use standard units. Power should be measured in watts, which are newton·meters per second. Kilograms are units of mass, not weight or force. The following adjusted version of the formula includes the multiplier 9.8 (the acceleration of gravity in m/sec²), which converts kilograms to newtons, yielding power in watts (N·m/s).

$$\text{POWER}_w = (\sqrt{4.9})(9.8)(\text{BODY MASS}_{kg})(\sqrt{\text{JUMP-REACH SCORE}_m}) \quad (2)$$

Another problem is that the texts never specified whether the formula estimates peak or average power. However, the following analysis shows that the power obtained is the average power exerted by gravity on the jumper's body as it falls back to the ground from the jump high point. Using standard equations of projectile motion (2) to describe the fall of the jumpers center of mass (CM) from its high point to where the foot contacts the ground

$$H = V_0t + \frac{1}{2}gt^2 \quad (3)$$

where: H = distance (m) the CM descends from its high point
(same as jump height, or rise of the CM to its high point)

V_0 = CM vertical velocity (m/s) at the start of its descent
 t = time (s) taken for the CM to descend from its high point
 g = acceleration of gravity (m/s²)

Because vertical CM velocity is zero at the jump high point, substitution of appropriate values in equation 3 yields:

$$\begin{aligned}
 H &= (0)t + \frac{1}{2}(9.8)t^2 \\
 t &= \sqrt{H} / \sqrt{4.9}
 \end{aligned} \tag{4}$$

Describing the average velocity (V_{AV}) of the CM during its descent:

$$V_{AV} = H / t$$

Substituting the value of t from equation 4:

$$V_{AV} = H / (\sqrt{H} / \sqrt{4.9}) = \sqrt{H} \cdot \sqrt{4.9} \tag{5}$$

Since power is equal to force times velocity, the average power (P_{AV}) exerted by the force of gravity on the jumper's body as he falls back to

the ground after reaching the high point of the jump equals body weight (body mass times the acceleration of gravity) times the average velocity of

the CM during its descent:

$$P_{AV} = \text{Force} \cdot V_{AV}$$

$$P_{AV} = 9.8(\text{BODY MASS})(\sqrt{H})(\sqrt{4.9}) \quad (6)$$

It can be seen that, with some shuffling of terms, the above equation is exactly the same as the Lewis formula (equation 2) showing that power calculated from the formula is that exerted by gravity on the jumper's body as it falls back to the ground from the jump high point. The only apparent connection between the latter power and the power exerted by the jumper while he is taking off from the ground is that both are greater for higher jumps. In telephone conversation, Dr. Mathews confirmed that the formula provides only the average power of the falling jumper and not the power exerted by the jumper while taking off. He confirmed the need for a method to determine the power produced during the jumping takeoff phase.

METHODS

In order to evaluate the validity of the Lewis formula and, to develop an improved prediction equation if needed, data was collected on 17 male subjects performing the jump-and-reach test and jumps from the surface of a force platform, the latter of which enabled direct measurement of jumping power output. Table 1 describes the test subjects, all of whom signed an informed consent document.

[TABLE 1 ABOUT HERE]

The jump-and-reach test

Each subject had his right finger tips marked with orange chalk. He stood with a wall at his right side, reached up as high as possible with his right hand, and marked the wall while keeping his left arm down and feet flat on the floor. He then assumed a bent-knees preparatory position, paused, and jumped as high as possible, touching the wall again with his fingers. The jump-and-reach score was the vertical distance between the two marks. Each individual performed 2-3 submaximal practice jumps, then jumped for maximal height 3 times. The highest score obtained was used to calculate power output using the Lewis formula.

The force platform jumps

Standing on an AMTI (Newton, MA) 0.6 m x 1.2 m force platform, each subject assumed a knees-bent preparatory position, paused, and jumped as high as possible, so that the movement was very similar to that during the jump-and-reach test. A continuous voltage signal from the force platform, proportional to the vertical force exerted by the jumper's feet, passed through an AMTI amplifier, and was digitized (converted to numerical representation) 500 times per second by an Infotek (Anaheim CA) model AD200 12-bit analogue-to-digital converter board mounted in a Hewlett Packard (Lexington, MA) model 310 desktop computer.

Power output of the jumper was calculated as the product of force and velocity. Force exerted by the jumpers muscles resulted in vertical ground reaction force (VGRF) at the feet which could be considered to act at the total body center of mass (TBCM), accelerating the body upwards. The power value of interest in jumping then was the product of VGRF and TBCM vertical velocity (VV).

$$\text{JUMPING POWER}_w = \text{VGRF}_N \cdot \text{TBCMVV}_{\text{m/s}} \quad (7)$$

VGRF was obtained continuously throughout the jump from force platform output. TBCMVV had to be calculated, using the principle that impulse equals change in momentum, or force multiplied by time equals

change in the product of mass and velocity. In the case where mass doesn't change during the time that force is applied:

$$\text{force} \cdot \text{time} = m \cdot \Delta V$$

and

$$\Delta V = \text{force} \cdot \text{time} / \text{mass}$$

For the jumpers, change in TBCMVV during each sampling interval equalled the VGRF acting on the body multiplied by the time period (t) over which the force was applied divided by body mass (BM):

$$\Delta \text{TBCMVV}_{m/s} = \text{VGRF}_N \cdot t / \text{BM}_{kg} \quad (8)$$

The force used for the velocity calculation was the VGRF reading from the force platform minus body weight, since it is *net* vertical force which results in changes in vertical velocity of the jumper's body. Absolute TBCMVV was updated at the end of each 500th-of-a-second time interval by adding ΔTBCMVV to the velocity at the start of the interval, starting at zero velocity at the beginning of the jump. Instantaneous power was calculated throughout the jumping movement as the product of VGRF and the calculated TBCMVV. Average power was calculated over the time period between initiation of the jump movement and takeoff. All processed

data were transferred to a VAX 780 main-frame computer for statistical analysis using BMDP (Berkeley, CA) statistical software. The following BMDP procedures were used: 1D for descriptive statistics, 8D for correlations, and 1R for multiple linear regressions. Figure 1 shows VGRF, TCBM vertical position and velocity, and power-output during a jump. TBCM position ended higher than where it started because the jumper began in a semi-squat position and ended up standing erect.

RESULTS

Jumping power calculated from the Lewis formula respectively correlated 0.83 and 0.72 with force-platform determined peak and average power and underestimated them by $70.1 \pm 3.5\%$ and $12.4 \pm 18\%$ respectively (Table 2). The low standard deviation for Lewis power suggests the formula minimized individual differences.

[TABLE 2 ABOUT HERE]

Regression analysis

A multiple regression procedure was used in order to determine if a more effective equation than the Lewis formula could be developed for

estimating power from jump-and-reach distance and body mass. The resulting equations were:

$$\text{Peak power(W)} = 61.9(\text{jump height(cm)}) + 36.0(\text{body mass(kg)}) + 1822 \quad (9)$$

$$\text{Average power(W)} = 21.2(\text{jump height(cm)}) + 23.0(\text{body mass(kg)}) - 1393 \quad (10)$$

Correlations between observed and equation-predicted peak and average power were 0.88 and 0.73 respectively. These equations produced accurate peak and average power group means, and respective standard deviations of 603 W and 247 W, which more closely reflected actual inter-subject variability than did the Lewis power standard deviation.

DISCUSSION

Despite their increasing use, the Lewis formula and nomogram have never been supported by a scientific journal publication and are not valid instruments for estimating either peak or average power generated by a subject performing a jump. The formula actually calculates the average power exerted by the force of gravity on the body as it falls from the jump high-point to the ground, which has no direct theoretical connection to peak or average power exerted by the muscles as they generate force on the ground during the jump takeoff phase.

In the present experiment, test results were used to develop regression equations to estimate peak and average power during jumping,

using jump height and body mass for input. The equations produced very good estimates of peak power during jumping and fair estimates of average power.

It is recommended that further experimentation be done to produce equations based on the test results of a large group of subjects, including males and females of different ages and levels of physical ability. This would establish definitive power-output estimation equations and help determine whether one set of equations is adequate for diverse populations or whether population-specific equations would provide more accurate estimations. The former would be a preferable outcome. In future testing, the jump-and-reach test should be performed directly from the force platform surface so that power output and a jump-and-reach score can be obtained from the same jumps.

PRACTICAL APPLICATIONS

Use of the Lewis formula and nomogram should be discontinued because they do not provide accurate estimates of either peak or average power produced by the muscles during a jump. The equations presented herein provide a reasonable alternative to the Lewis formula for jumping power-output estimation until such time that new regression-equations can be developed on a large and diverse subject population, using similar

methodology. The equation estimating *peak* jumping power from body mass and jump height is particularly effective and can be used in conjunction with other tests to screen applicants for athletic teams and physically demanding jobs. It can also be used to monitor progress among participants in physical training programs (e.g. athletes, military personnel, students in physical-education classes, and fitness club members). The test requires little equipment and is easy, quick, and inexpensive to administer.

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TEXT TO FIGURES

Figure 1. Key jump parameters. Upper graph: solid line = power; dashed line = TBCM vertical position. Lower graph: solid line = VGRF; dashed line = TBCM vertical velocity. Vertical lines: a. TBCM begins upward movement, b. feet leave platform, and c. feet re-contact platform.

Table 1. Subject characteristics (mean \pm sd)

| | |
|-----------------------|--------------------------------|
| n | 17 |
| gender | male |
| age (yrs) | 28.5\pm6.9 |
| height (cm) | 179\pm5.4 |
| body mass (kg) | 74.7\pm7.7 |

Table 2. Lewis and force-platform measured powers

| | <u>Mean±SD</u> |
|---|----------------|
| Lewis formula calculated power (W) | 1,107±144 |
| Force platform measured peak jumping power (W) | 3,767±686 |
| Force platform measured average jumping power (W) | 1,325±341 |

NOTE ON U.S. ARMY HUMAN RESEARCH

The views, opinions, and/or findings contained in this report are those of the authors and should not be construed as an official Department of the Army position, policy, or decision.